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Summer thermal comfort and [overheating health](#) in the elderly

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Abstract

Atypically warm summers such as 2003 and 2018 are predicted to become normal by 2050. If current climate projections are accurate this could cause heat-related mortality to rise by 257% by 2050, the majority of which will be in vulnerable groups such as the elderly. However, little is known about the temperatures achieved in the homes of the elderly even in typical summers, and even less on whether these are comfortable. This study examines, for the first time, the validity of current thermal comfort models in predicting summer comfort levels in the 65+ demographic over a typical and an atypically warm summer. This was achieved through the first longitudinal study of thermal conditions in homes of the elderly in the [South West](#) UK, utilising repeated standardised monthly thermal comfort and health surveys with continuous temperature monitoring in both living (LR) and bed rooms (BR). Results show that neither the PMV/PPD model (ISO 7730) nor the adaptive model (ISO 15251) accurately predict true thermal comfort in our sample. Overheating analysis using CIBSE TM59 (based on ISO 15251) suggests significantly more homes (50% LR, 94% BR = 94% overall) overheated during the atypically warm summer, compared to the typical summer (3% LR, 57% = 57% overall). These are worrying results, especially for the elderly, given the projected increases in both the severity and frequency of extreme summers in a future, changed, climate.

Keywords: Ageing Population, Thermal Comfort, Overheating, Temperature Monitoring, Health

Practical Application

This paper provides new data on the performance of the homes of the elderly in both a typical and atypically warm summer. Our results could be considered for building performance evaluation in homes with elderly occupants to mitigate overheating risk. Crucially, we not only examine the impact of CIBSE criteria on these homes, but also look at thermal acceptance, which is important to understand the true impact of elevated temperatures in this demographic.

1. Introduction

Projections estimate that the global average surface temperature is likely to rise by up to 5.4°C by 2070 [1]. As a result, the frequency, duration and intensity of high external temperatures

are likely to increase, and atypically warm summers such as 2003 and 2018 are predicted to become normal by the middle of the century [2]. The heatwave of 2003 resulted in 70,000 deaths across Europe [3], 2,000 of which were in the UK [4], and the heatwave of 2018 is likely to have caused additional deaths, though estimates are not yet available. [Predictions](#)[Estimates](#) suggest that heat-related mortality could rise by an estimated 257% based on a current baseline of 2000 deaths, if current temperature projections are accurate [2]. Consequently, there is increasing concern over the impact of more frequent heatwaves on morbidity and mortality [6, 7], particularly in vulnerable groups such as the elderly [8].

This is because the elderly are known to be most vulnerable to extreme temperatures, with suggestions that between 82% and 92% of summer mortality occurs in the 65+ demographic [7]. Ageing impairs the thermoregulatory system, causing a deterioration in the body's physical response to temperature change, meaning that older people are less able to rapidly cool their bodies during hot weather, leading to morbidity [9, 10]. Furthermore, chronic illnesses are more prevalent in older people [11, 10], and those with cardiovascular, respiratory or mobility problems are said to be most at risk of heat related morbidity and mortality [12]. This can be worsened by medications interacting with personal thermoregulation [9]. The 2003 heatwave resulted in the UK Government releasing a heatwave plan [13], with the primary aim of reducing summer mortality by providing guidance and specific measures for vulnerable groups. Advice includes staying out of the heat, keeping cool and maintaining a cool environment [13]. However, despite this, it is suggested that older people do not always recognise their vulnerability [8], and consequently do not prepare adequately for heatwaves.

Despite the relatively temperate climate of the UK, much of the current morbidity and mortality is associated with overheating in internal environments [14, 15], which is concerning given that older people are believed to spend between 85% and 95% of their time in their homes [16] conducting predominantly sedentary activities [11]. Hence, there is a clear need to ensure their homes can be kept at temperate conditions to maintain health. However, the housing of older people is believed to exacerbate health problems [17]. Despite recognition that housing design is an important factor in reducing heat-related mortality [10], older people are more likely to be living in sub-optimal houses that are prone to overheating in comparison to younger people [16].

Few studies have investigated the thermal comfort of residential homes during summer periods [18] and none have focused on the elderly despite their increased vulnerability. Much of the current literature uses dynamic thermal modelling (DTM) to focus on overheating of newbuilds or post retrofit [19], low-income households [20, 21], how building fabric influences internal temperatures [22, 23], the vulnerabilities in the current housing stock that might lead to future overheating [24, 25, 26], and the influence of occupants on overheating risk [27]. Furthermore, some studies recognise that a lack of air conditioning can lead to increased heat-related illness [28], but this is currently not a significant problem in the UK, as only approximately 3% of homes have air conditioning [29]. However, this is predicted to change, with passive ventilation strategies predicted to become inadequate by 2050 [30]. Currently, there is no clear link between heat-related morbidity and mortality and socio-economic status [31], however, if air

conditioning becomes increasingly necessary then not only will this increase carbon emissions, but it will put pressure on low income households who may not be able to afford sufficient cooling. Older people are known to have lower incomes than that of the working age population, which may create summertime fuel poverty.

Furthermore, the UK population is ageing and by 2050, 25% of the UK population is expected to be aged 65 and over, compared to 18% in 2018 [32]. The greatest population increases are expected to occur in the 80 years and older categories [33]. Worryingly, increasing longevity will result in a higher number of older people suffering the morbidity and mortality associated with high temperatures.

Overall, it is likely that there is a strong association between morbidity and mortality in the elderly due to the indoor environmental conditions in their home. However, very little is known about the precise nature of thermal conditions in homes occupied by people aged 65 and over, especially whether they find the internal conditions of their home in summer to be comfortable. This paper sets out to address this gap.

We first briefly introduce the assessment of thermal comfort using the PMV and Adaptive standards, followed by a discussion of current overheating criteria and evidence from other field studies, in Section 2. This is followed by Section 3 which describes our methods for the field study underpinning the data in this paper. Section 4 discusses the results of our field study compared against the PMV/PPD and Adaptive models and the TM52 and TM59 overheating metrics. Finally, Section 5 sets our results in context of the current state of the art and points to future work.

2. Current standards for thermal comfort and overheating

‘Thermal Comfort’ is the term used to describe a balance of environmental and personal factors that lead to a person feeling satisfied and comfortable in their thermal environment [34]. Two key approaches for assessing thermal comfort are the ‘PMV-PPD’ model [35] and the ‘adaptive’ model [36]. Methods to calculate the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) are described in ISO 7730 [37] and ASHRAE Standard 55 [38] and can be used for mechanically ventilated and heated buildings as well as free running buildings. ASHRAE Standard 55 also describes the use of the adaptive model (in free running buildings only), whose European counterpart, with a slightly different formulation, is described in BS EN15251 [48].

The differences between these models and their general applicability are well-known in the literature [74], and briefly summarised in Table 1. What is pertinent here is their applicability to the elderly demographic. In terms of model inputs, the personal variables clothing insulation (CLO) and metabolic rate (MET) can be adjusted in PMV suitably to account for differences in clothing or lowered metabolic rates in the elderly, whereas the adaptive model has no specific input adjustments for the elderly. The PMV model and the adaptive models specify different acceptability limits implying narrower temperature bands for vulnerable groups,

including the elderly. Since the ASHRAE standard does not have the tighter range of $-0.2 < \text{PMV} < +0.2$, it prescribes the $-0.5 < \text{PMV} < +0.5$ as applicable to the elderly, in contrast to EN 15251, which uses the ± 0.2 band. Hence, the embodiment of these conditions in the ASHRAE 55 adaptive model (90% acceptability) corresponds to those for typical conditions in BS EN 15251 (Category II), implying the lack of a one-to-one correspondence between the standards. It is noteworthy that both adaptive standards claim applicability for conditions for near sedentary activities where $\text{MET} \in [1, 1.3]$, whereas the elderly are known to have a lowered metabolic rate (around 0.9 [40]). Nonetheless, we use the recent CIBSE overheating standard for homes (TM59 [49]), which is based on the adaptive standard, as it claims general applicability including for vulnerable occupants such as the elderly.

Table 1: Application of current thermal comfort standards to the elderly.

Category	PPD (%)	PMV	t_o Upper Limit (°C) [‡]	t_o Lower Limit (°C) [‡]	Explanation
I	< 6	$-0.2 < \text{PMV} < +0.2$	$0.33t_{rm}+20.8$	$0.33t_{rm}+16.8$	High level of expectation; recommended for spaces occupied by very sensitive and fragile persons with special requirements like disabilities, very young children and elderly persons.
II	< 10	$-0.5 < \text{PMV} < +0.5$	$0.33t_{rm}+21.8$	$0.33t_{rm}+15.8$	Normal level of expectation and should be used for new buildings and renovations. This category is equivalent to the 90% acceptability category in ASHRAE 55, and hence applies to the elderly in that standard. Note that ASHRAE 55 uses monthly mean outdoor temperature not t_{rm} (not shown for brevity).
III	< 15	$-0.7 < \text{PMV} < +0.7$	$0.33t_{rm}+22.8$	$0.33t_{rm}+14.8$	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	> 15	$\text{PMV} < -0.7$ or $+0.7 < \text{PMV}$			Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

[‡] t_o is the operative temperature, t_{rm} is the exponentially weighted running mean outdoor temperature per [48].

2.4 Overheating criteria

CIBSE TM 59 provides the most recent criteria to ensure comfort and prevent overheating [49], based on one of three criteria in CIBSE TM52 [50] and one in CIBSE Guide A [51]. This applies to homes that are predominantly naturally ventilated, a condition met by all the homes in our sample. TM52 criteria are evaluated against ΔT , which is defined as:

$$\Delta T = t_{op} - t_{max}$$

Where

T_{op} is the hourly indoor operative temperature

T_{max} is the upper limit for Categories I or II in Table 1

TM59 uses the first criterion for overheating from TM52, which defines the Hours of Exceedance (H_e), representing the *duration* of overheating:

$$H_e = \sum h \forall \Delta T \geq 1^\circ C$$

The summation is performed over all occupied hours (h) as defined for the type of building. H_e should not exceed 3% of occupied hours for the months May to September inclusive. TM59 refines this criterion for domestic application and adds a separate and additional criterion from CIBSE Guide A for bedrooms as shown in Table 2.

Table 2: CIBSE TM59 criteria for assessing overheating risk in free running domestic buildings.

Criterion 1A	Criterion 1B
Living Rooms, kitchens and bedrooms	Bedrooms only
TM52 Criterion 1 is evaluated with occupied hours set to the range [09:00, 22:00] for living rooms and kitchens and 24 hours for bedrooms.	To guarantee comfort during the sleeping hours the operative temperature in the bedroom between [22:00, 07:00] shall not exceed 26 °C for more than 1% of annual hours.

TM59 notes that homes can fail the remaining two criteria from TM52 and still meet the overheating standard. We describe these for completeness:

Criterion 2. *Daily weighted exceedance (W_e)*: deals with the severity of overheating within any one day, which can be as important as its frequency. The W_e threshold is ≤ 6 per day. Where:

$$W_e = (\sum h_e) \times WF$$

$$= (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$$

And:

$$WF = 0 \forall \Delta T \leq 0, \text{ else } WF = \Delta T$$

$$h_{ey} = \text{hours when } WF = y$$

Criterion 3. *Upper limit temperature*: sets an absolute maximum daily temperature ($\Delta T \leq 4K$) for a room, beyond which the level of overheating is unacceptable.

2.5 Field Studies

In the context of this study, it is noteworthy that the above criteria do not discriminate between vulnerable and non-vulnerable occupant groups as very little is known about appropriate threshold temperatures or acceptable durations of overheating in vulnerable populations such as the elderly. This is because, surprisingly little is known about the achieved internal temperatures in such homes and their acceptability to the occupants. This is particularly important given that a disproportionate rate of morbidity and mortality occurs in the elderly demographic. There are very few domestic summer temperature monitoring studies, as most focus on winter temperatures where the associated mortality tends to be an order of magnitude greater than summer mortality. However, as global temperature increases, the instances of summer mortality are likely to increase and consequently the importance of understanding the internal environment of those most at risk, including the elderly, will become more significant. To date there have been a small number of UK temperature monitoring studies, of varying sample sizes, as summarised in Table 3.

Table 3: Chronological summary of domestic summertime temperature monitoring studies in the UK.

Study	Period	Sample size	Coverage	Sensor Type	f	Overheating Metric	t_{LR} (°C)*	t_{BR} (°C)*	SES	Include Elderly
Summerfield [52]	Feb '05 to July '06	15	Milton Keynes	HOBO U12-012	10-30		19.8	19.3	No	
Beizaee [25]	July '07 to March '08	207	England	HOBO UA001-08	45	CIBSE Guide A, BS EN 15251	21.8	21.6	Yes	
Oraiopoulos [56]	Summer '09	230	Leicester	HOBO Pendant	60		22.2	22.4	No	Yes
Lomas [24]	July '09 to March '10	248	Leicester	HOBO UA001-08	60		16.4		Yes	Yes
Pathan [18]	Summer '09 to Summer '10	122	London	HOBO U12-012	10	ASHRAE 55				
EFUS [75]	Summer '11	823	England	TinyTag Transit	20				Yes	Yes
Sameni [54]	Summer '11 to '12, '13	25	Coventry		60	TM 52	25 [†]		No	
Gupta and Kapsali [57]	2013	6	SE England		5	Guide A TM52	21-24		Yes	
Jones [58]	Summer '13	3	SW England	HWM Ecosense	5	Guide A ISO 15251	24	24	No	
Baborska-Narozny [55]	April '13 to April '14	20	Leeds	iButton	30	Guide A	23.4		Yes	

Vellei [59]	Summer '14	46	Exeter, UK	5	TM 52	23.9	Yes	No
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Notes:

f is sampling frequency in minutes

* LR is living room and BR is bedroom

t is mean summer temperature

† estimated from graph

SES whether a thermal comfort or other socio-economic survey was undertaken

2.6 Research Questions

The literature review suggests that there is inadequate evidence on the effect of the indoor thermal environment on the elderly. Little is known about what temperatures are achieved ~~and~~, whether or not the occupants are comfortable at the achieved temperatures ~~and what effect this has on health~~. This is especially concerning given that this demographic is most at risk and increasing most rapidly in comparison to other age classes in the population.

Consequently, this paper addresses ~~two~~^{three} key questions:

1. Do the temperatures achieved in the homes of the elderly meet the PMV-PPD, Adaptive and TM59 standards for a typical summer and an atypically warm summer?
2. Are the temperatures achieved in the homes of the elderly considered comfortable by the occupants?
3. ~~Is participant health worse in an atypically warm summer compared to a typical summer?~~

4.03.0 Methodology

This section describes the longitudinal temperature monitoring study designed to address the above research questions. The study was conducted in the city of Bath, South-West UK, with participants living within a three mile radius of the city. Given the increased vulnerability of older people to extreme heat, the only requirement for participation was to be aged 65 or over. A total of 43 homes with of 59 occupants were recruited. Of these, 37 homes were used for analysis in the first summer, and 16 homes in the second summer¹. Each home designated one person to respond to the surveys, which were disseminated monthly, to ensure continuity. The mean age of our sample is 76.3 years (n = 59, s = 9.1 years). The methods are reported further in Appendices A and B.

4.13.1 Sensors

Two sensors were placed in each home:

- living room sensor
- bedroom sensor

The living room sensor measures both temperature and humidity and the other two sensors measure temperature². Sensors that measure both temperature and humidity are considerably more expensive than temperature sensors, so this was judged the optimal combination to enable humidity to be recorded for the PMV calculations whilst sufficiently equipping each of the participating homes. Sampling frequency was set to 90 minutes (i.e. 16 readings/day) due to the total memory capacity of the sensors. CIBSE TM59 criteria use operative temperature (T_{op})

¹ The reduction in participating homes is due, in part, to a natural drop in participant retention (as these homes were also part of a winter field study, reported elsewhere), sensor failures and relocation, declining health or death.

² Only 6 living rooms in 2018 were fitted with temperature + relative humidity sensors, the remaining being temperature only.

which depends on both air temperature (T_a) and mean radiant temperature (T_m), whereas our sensors only measure T_a . T_m can be affected by both high radiant temperatures and elevated air velocity (V_a) as these alter the radiant and convective exchanges for the standard black globe thermometer usually used to undertake measurements. We assessed the likely impact of these through a transverse survey in November 2016 using the ISO 7730 compliant Swema equipment, covering the 30 homes that had joined our study by that date. A regression of T_a and T_m showed a strong correlation ($R^2 = 0.96$), suggesting that T_a is a good proxy for T_m . Measurements of air velocity taken at the same time indicated that all but three homes had $V_a < 0.1 \text{ ms}^{-1}$, with $V_{a_max} < 0.15 \text{ ms}^{-1}$. These results are supported by the literature suggesting that, in practice, the difference between T_a and T_m , even in summer, tend to be small [70,79] and hence T_a can be taken as a good approximation of T_{op} . Nonetheless, as this paper reports summer conditions when greater variations in T_m and V_a could be expected, our results should be read in context of the assumption that $T_{op} = T_a$.

4.3.2 Surveys

The survey had the following key features:

- The survey was designed to assess both thermal comfort and health. The thermal comfort survey was based on a reduced set of the standard survey design contained in ASHRAE 55 and commonly used in other studies [60, 48, 38], including information necessary for PMV-PPD calculations such as CLO values. Health metrics were adopted from the NHS Health Survey for England [61], the Short Form-36 Questionnaire [62] and the ‘Older People’s Quality of Life Questionnaire’ [63].
- Although no time was set for answering the questions, the surveys were almost exclusively answered in the daytime and hence reflect daytime comfort.
- Although initial surveys were returned at a fortnightly frequency, the response rate settled to a monthly frequency. The overall return rate was high at 75.9%.

4.3.3 Summer Weather

Surveys and monitoring occurred over the summers (June - September) of 2017 and 2018. Figure 1 shows the mean summer temperatures recorded between 2001 and 2018 for the UK, South-East and South-West England, where the temperature monitoring took place. The average temperature across all years is 14.7°C ($s = 0.61^\circ\text{C}$) for the UK, 16.71°C ($s=0.69^\circ\text{C}$) for the South-East and 15.4°C ($s = 0.66^\circ\text{C}$) for the South-West, with 2003, 2006 and 2018 being atypically warm (i.e. at least 1 standard deviation greater than the mean). In Bath (where monitoring took place) summer 2017 averaged 15.5°C and summer 2018 averaged 17.1°C . Hence, the summer of 2017 is representative of a typical summer whilst that of 2018, an atypically warm summer, further evidenced in Figure 2.

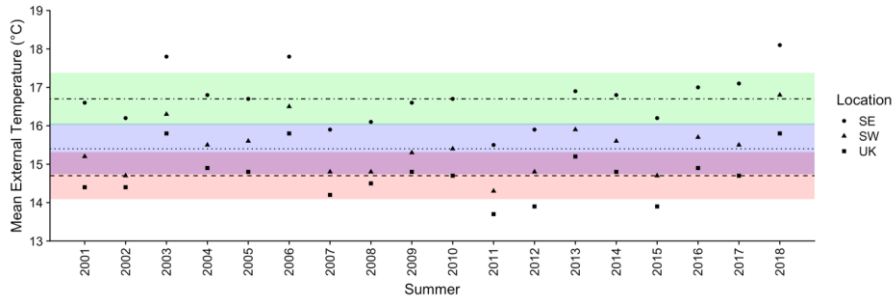


Figure 1: UK, South East and South West England summer mean external temperatures between 2001 and 2018. Horizontal lines and colours indicate UK (dashed, red), SE (dot-dashed, green) and SW (dotted, blue) means and standard deviations [64]. The purple area is the overlap between UK and SW standard deviations. Note that in the South West, 2017 was representative of an average summer whereas 2018 was well outside one standard deviation.

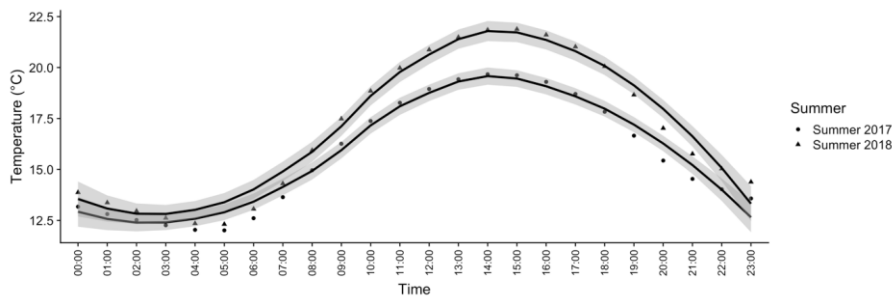


Figure 2: Hourly mean temperature for summer 2017 and 2018, with 95% confidence interval (grey band).

External weather data for Bath was obtained from two sources: the Copernicus Atmosphere Monitoring Service (CAMS) [76] and the Modern-Era retrospective analysis for Research and Applications (MERRA) [77]. Data was sourced for the entire duration of the study (June – September 2017 and June – September 2018) at hourly intervals.

5.04.0 Results

Box-plots for hourly internal living room and bedroom temperatures for each home across the two summers (2017 and 2018) are shown in Figure 3. For summer 2017 the mean internal living room temperature was 21.2°C ($s = 1.2^\circ\text{C}$) and the mean internal bedroom temperature was 21.2°C ($s = 0.9^\circ\text{C}$) and for summer 2018 the mean internal living room temperature was 23.0°C ($s = 1.1^\circ\text{C}$) and the mean internal bedroom temperature was 23.3°C ($s = 1.0^\circ\text{C}$). A Pearson's Product Moment Correlation Coefficient of the two summers shows a weak positive correlation suggesting that the internal temperatures did differ significantly between the two ($r = 0.33$ for living rooms and $r = 0.34$ for bedrooms, $p < 0.05$ for both). Expectedly, the atypically

As overheating is influenced by maximum temperatures, Figure 5 shows the percentage of occupied hours (defined per Table 2) exceeding a range of internal temperatures for each dwelling split by room and year.

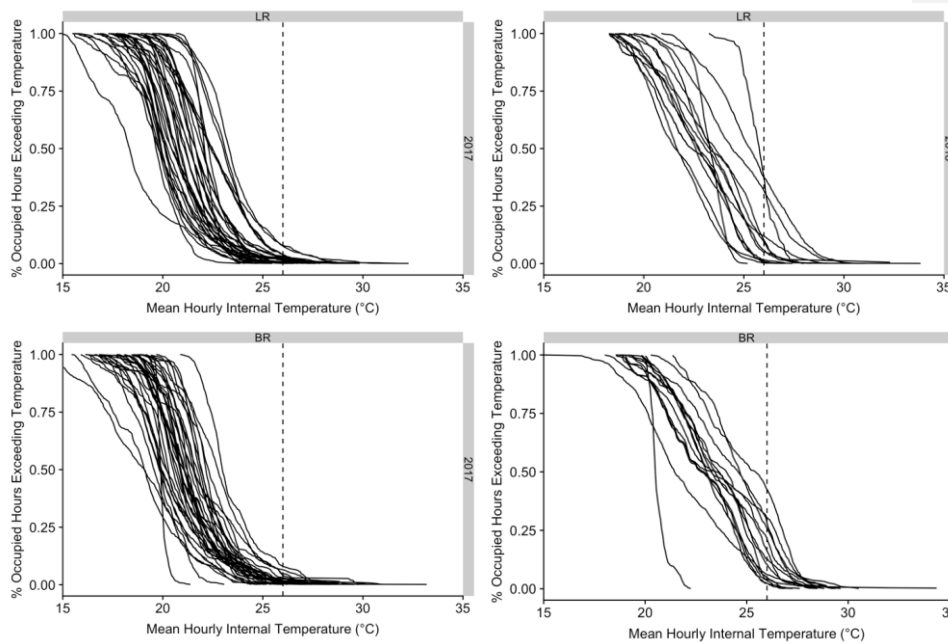


Figure 5: Percentage of occupied hours (calculated according to TM59 criteria per Table 2) exceeding a range of internal temperatures by room type and year. Living Rooms (LR) are in the top row, bedrooms (BR) in the bottom row with 2017 and 2018 in the left and right columns respectively. All graphs marked with 26°C threshold (dashed line) per TM59 guidance for bedrooms and PHE's Heatwave Plan for care homes (applied to Living Rooms in our data set). Note that the home with the identifiably different profile (e.g. in the 2018-BR plot) is a basement flat with high thermal mass and low solar gains.

We observe that, as expected, more homes have longer durations of overheating in the atypically warm summer compared to the typical summer. For living rooms, although there is no specific guidance on internal temperatures for homes, sources such as Public Health England's Heatwave Plan [78] suggest that internal areas in care homes (known to be occupied by a similar demographic to our sample) should be kept below 26°C, hence, we use this as a guideline. In the typical summer of 2017 we observed that of the homes exceeding the 26°C limit, they did so for a maximum of 10% of occupied hours, whereas for 2018 this rose to 38% of occupied hours. For bedrooms, homes shown to exceed the 26°C limit did so for a maximum of 8% of occupied hours in the typical summer of 2017, however, this increased to a maximum of 42% of occupied hours in the atypically warm summer of 2018. This is concerning given that occupants were exposed to significantly longer periods of overheating in the atypically warm summer, especially in bedrooms where they are less able to adapt their environment when sleeping.

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4.1 Thermal Comfort

In the surveys, participants responded with their Thermal Sensation Vote (TSV), which measures how comfortable they felt in their home, using the widely used Bedford Thermal Comfort scale (Table).

Table 4: Bedford Thermal Comfort Scale.

Response	Scale
Much too warm	3
Too warm	2
Comfortably warm	1
Neither warm nor cool	0
Comfortably cool	-1
Too cool	-2
Much too cool	-3

The following sections compare TSV data against both PMV-PPD and Adaptive model predictions.

4.1.1 PMV-PPD Approach

Figure 6 shows normalised density plots for the self-reported TSV and the model predicted PMV. Taking $TSV \in [-1, 1]$ as comfortable, we get 91% of votes for summer 2017 and 89% for 2018 falling in this category³. Mean PMV_{2017} was -1.2 whereas mean TSV_{2017} was +0.1; and mean PMV_{2018} was -0.5 whereas mean TSV_{2018} was +0.3.

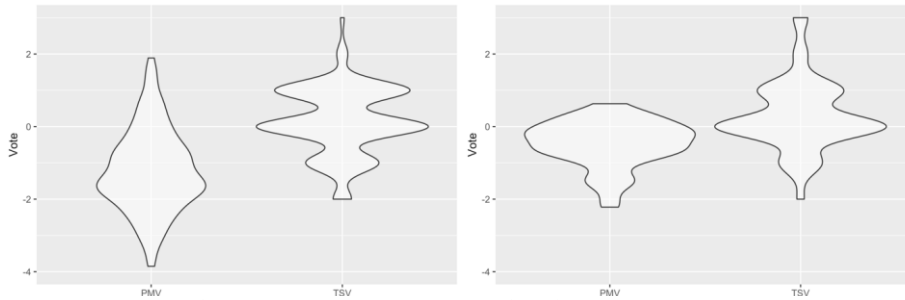


Figure 6: Density plots for TSV and PMV, in summer 2017 (left) and summer 2018 (right).

From this, two inferences are drawn: (i) occupants were broadly comfortable in both the typical and the atypically warm summer, suggesting adaptation is in play and (ii) PMV tends to predict

³ Although Categories I and II of the standards specify votes in the range $[-0.2, +0.2]$ and $[-0.5, +0.5]$ respectively as comfortable, our surveys are on an ordinal scale. The effect of taking comfort to be between $[-1, +1]$ is mitigated through the observation that the majority of votes in both summers were neutral (i.e. 0): 42% for 2017 and 52% for 2018. This minimises the risk of biasing the comfort band in either direction.

colder sensations than observed. Poor Spearman's rank correlations between PMV and TSV for both summers ($\rho = -0.06$ for 2017 and $\rho = 0.25$ for 2018), supports the latter conclusion.

4.1.2 Adaptive Approach

Figure 7 shows the results of applying the BS EN ISO 15251 adaptive model to our data. For the typical summer 2017, 30% of living room hours and 29% of bedroom hours were within Category I, which is considered acceptable for vulnerable occupants including the elderly, and 54% of living room hours and 55% of bedroom hours were within the Category II parameters. It is noteworthy that the majority of the remaining conditions are *below*, not above, the thresholds. For the atypically warm summer of 2018, 69% of living room hours and 66% of bedroom hours were within the adaptive Category I parameters and 86% of living room hours and 84% of bedroom hours were within the Category II parameters. This apparent "increase" in comfortable hours is due to the fact that the adaptive model thresholds are valid from 15°C t_{rm} (vertical line in the graphs), and that a significant proportion (27.6%) of 2017 hours were below this cut off.

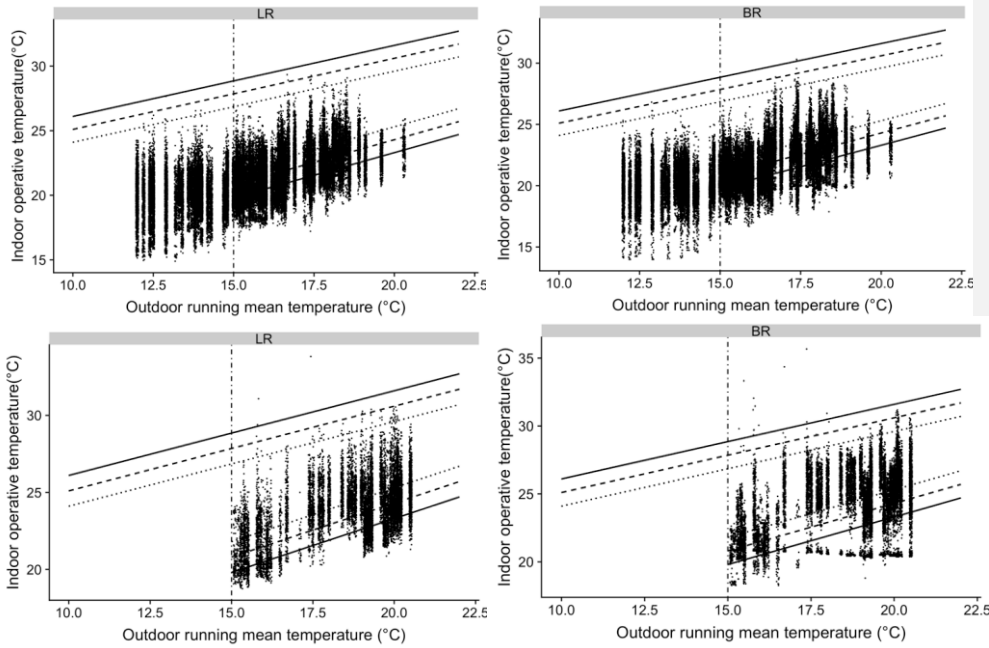


Figure 7: Outdoor running mean temperatures (°C) and indoor operative temperature (°C) for all participating homes in summer 2017 (top) and 2018 (bottom), split by room type (LR = living room, BR = bedroom), with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

Figure 8 plots TSV against the adaptive thresholds using a total of 114 votes (from 35/37 homes) returned in 2017 and 48 votes (from 16/16 homes) in 2018. For 2017, of the 91% self-reported responses within $TSV \in [-1, +1]$, 28.6% were within the Category I temperature limits and 56.1% within Category II limits. In summer 2018, of the 89% self-reported responses within $TSV \in [-1, +1]$, 53.5% were within the Category I limits and 72.9% within Category II. Again, we observe that TSV maps poorly to the thresholds set by EN 15251 with occupants in our sample finding a wider range of indoor temperatures comfortable, particularly those below

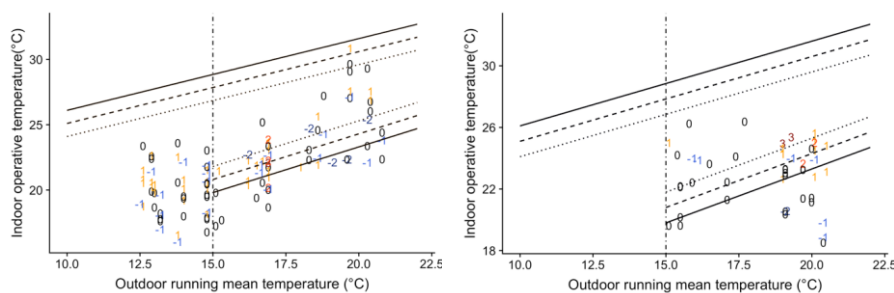


Figure 8: TSV for summer 2017 (left, $N = 114$) and summer 2018 (right, $N = 48$) with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. Coloured numbers represent TSV vote ranging from +3 (deep red), through 0 (black) to -3 (deep blue). The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

the lower thresholds.

4.2 TM59 Criteria

In order for a home to meet the TM59 criteria, it must meet TM52 Criterion 1 for all rooms and the CIBSE Guide A criterion for bedrooms only.

Figure 9 shows how each home performed against Criterion 1A, in each summer. Only one of the participating homes failed Criterion 1A in summer 2017, whereas 8 homes (50%) failed in

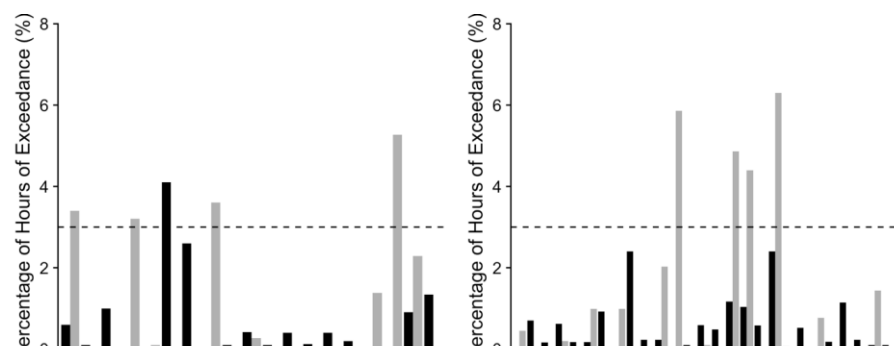


Figure 9: TM59 Criterion 1A: Percentage of hours of exceedance per home for 2017 (black) and 2018 (grey) in the living room (left) and bedroom (right), with 3% threshold (dotted line).

summer 2018. Note that we observe failures in either the bedroom (House IDs 20, 24, 25, 28) or the living room (House IDs 1, 6, 19, 33) but never both.

Figure 10 shows TM59 Criterion 1B for bedrooms. In summer 2017, ~~214~~ homes (57%) exceeded 26°C for over 1% of time and therefore failed the criterion, whereas for 2018, ~~152~~ homes (94%) failed the criterion. Mean percent hours of exceedance in 2017 were 1.8% above 26°C whereas this increased to 6.6% in 2018.

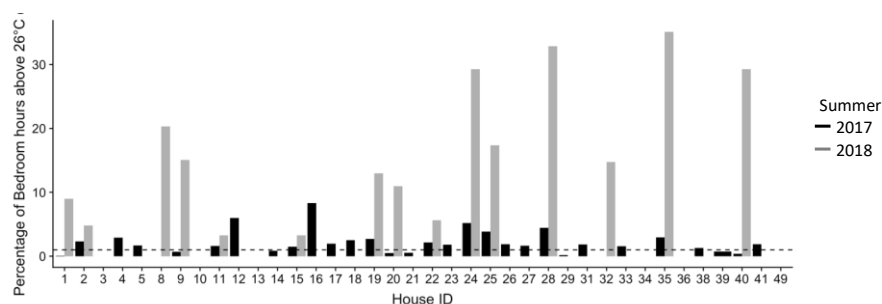


Figure 10: TM59 Criterion 1B: Percentage of bedroom hours above 26°C per home for both summers, with 1% threshold (dotted line).

Overall, in the typical summer of 2017 only one home failed both TM59 criteria (2.7%) whereas in the atypically warm summer of 2018, 5 homes failed both criteria (31.3%). This suggests that the choice of *either* criterion failing being sufficient to fail the standard as a whole is correct in order to minimise overall risk. All homes that failed Criterion 1A also failed Criterion 1B, suggesting that the latter standard may be sufficient to identify overheating on its own.

4.3 TM52 Criteria

Here we analyse compliance against criteria 2 and 3 of TM52. Though the TM59 standard does not mandate such compliance, we include them for completeness and to assess whether other risks, particularly those emanating from severity of overheating are evident in our data. Criterion 2 measures the severity of overheating using the daily weighted exceedance, which should not exceed 6 in any one day. Figure 11 shows, for each home, the number of days when the daily weighted exceedance > 6 in each summer. The failure rate for 2017 was 24% and 50% for 2018.

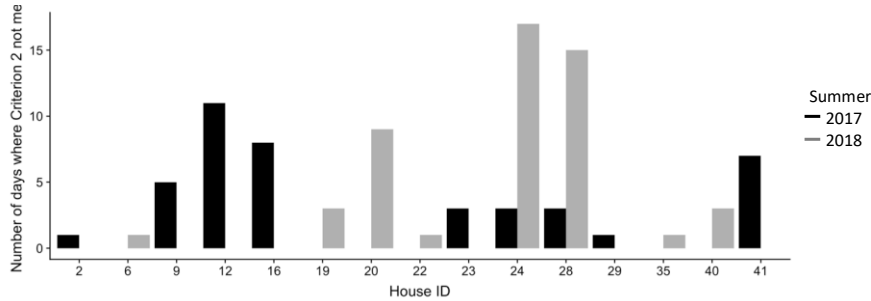


Figure 11: Number of days for each home where the daily weighted exceedance (Criterion 2) was not met.

Figure 12 shows that the upper limit temperature (Criterion 3) was exceeded in 14% of homes in 2017 and 31% in 2018. Analysis at the dwelling level suggests that all homes failing TM52 Criterion 2 also failed both TM59 Criteria. Only one home failing TM52 Criterion 3 failed to be identified in either TM59 criterion (House ID 6), and indeed was not identified by TM52 Criterion 2 either. However, the fact that this home fails Criterion 3 on only 1 day, suggests that TM59 correctly leaves out Criteria 2 and 3 from TM52.

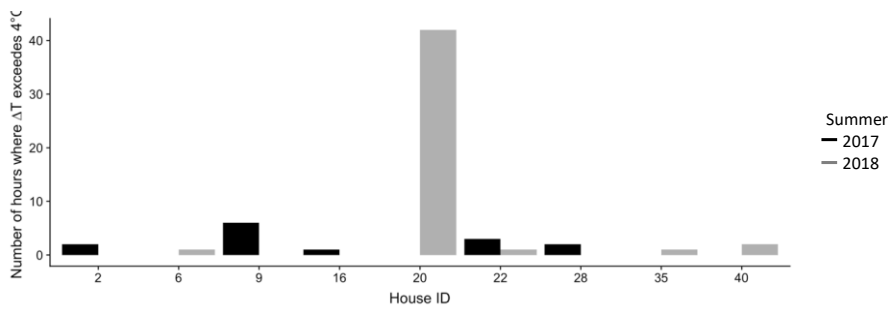


Figure 12: Number of hours per home where the internal temperature was 4°C above the upper limit.

5.0 Discussion and Conclusion

This paper has presented new data and analysis focusing, for the first time, on the summertime performance in the homes of the elderly located in the South West of the UK covering both a typical and an atypically warm summer.

With respect to thermal comfort, our results demonstrate that the PMV/PPD index is poor at capturing true comfort in both summers. For 2017 the PMV results suggested most people should have been feeling cold (with the majority of PMV outputs between $[-1, -2]$), whereas the TSV suggested that people felt comfortable, with 91% of votes between $[-1, +1]$. Although the strength of the correlation between PMV/PPD predictions and TSV for summer 2018 is slightly better than for summer 2017, PMV still suggests people would be feeling slightly cool with the majority in the range -1 to 0 . This discrepancy between PMV and TSV is perhaps not

surprising given that these homes are naturally ventilated, to which environment the PMV model is known to be less suited.

What is more surprising is the disconnect between the adaptive model and TSV data. Given that an average of 90% of the votes across both summers were within $[-1, +1]$ the fit of these votes to the adaptive model was, at best, 73%. Fit to Category 1, designed for vulnerable groups such as the elderly, was particularly poor with a maximum of 54% and falling as low as 29%. This discrepancy is harder to explain, but one key source of the problem could be the fact that homes form a very small fraction of the data used to derive the adaptive model.

Due to the fact that occupants did not always complete surveys during the most extreme periods, we rely on CIBSE TM59 for an analysis of overheating. Since overheating affects people differently during waking and sleeping hours, CIBSE TM59 defines separate tests for living rooms (Criterion 1A) and bedrooms (Criterion 1B). In our sample, only one home failed Criterion 1A in the typical summer of 2017 (3%) rising to eight in the atypically warm summer of 2018 (50%), showing a significant increase in overheating risk in the latter year.

However, the fact that 94% of bedrooms failed TM59 Criterion 1B in the atypically warm summer of 2018, i.e., had more than 1% of night-time hours at temperatures 26°C and above, is more worrying. Given that this was already at 57% in the typical summer of 2017 demonstrates that the problem may be more pervasive. Since failure in either criterion results in overall failure (i.e. for the entire dwelling) under TM59, the overall failure rates were also 57% and 94% in 2017 and 2018, respectively. Furthermore, these high failure rates for Criterion 1B subsume failures in 1A and the remaining two criteria in CIBSE TM52, suggesting that this metric alone may be sufficient to identify overheating risk, if it were deemed fit for purpose. However, given that our surveys were answered in the daytime and hence are not necessarily representative of thermal comfort during night time, a greater study of acceptable night time temperatures and their effect on quality and quantity of sleep is needed, given our results for the other rooms.

Based on the results of this study, we conclude that (i) there is a disconnect between existing models of comfort and the true experience of elderly and (ii) there could be severe risk of overheating in the homes of the elderly. This study suggests that the current models of comfort are not suitable for the elderly. Results suggest more data on the performance of the homes of the elderly, e.g. in more extreme weather or in locations that exacerbate warm weather such as dense urban centres, is needed to further investigate and improve understanding of the suitability of adaptive comfort and overheating in domestic settings for both day and night time, with specific relation to vulnerable occupants, such as the elderly.

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All data created during this research are openly available for the University of Bath data archive at <https://doi.org/dataset> created in Pure - upload data - DOI generated.

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Appendix A Participant selection

Bodily changes that result in a diminished ability to respond to temperature changes, exacerbating common health conditions, are said to commence around 65 years [65]. Hence, the main requirement was for participant age to equal or exceed 65 years. Exclusion criteria were designed to exclude those unable to give informed consent to participate in the study, or those whose lifestyle or behaviour is not representative of routine practice (based on [66]). This

included: (i) severe mental disability (ii) stroke or injury resulting in loss of speech and (iii) those who were bedridden or wheelchair bound.

A key question for longitudinal studies of this type is sampling frequency. An important consideration was participant recall since the aim was also to observe changes in health metrics over the sampling interval (such as number of GP visits, onset of temperature-related illness); so sampling frequency had to account for participants' ability to remember what had occurred over each sampling interval. Clearly, the more frequent the sampling, the better the recall, but also the greater the risk of participant fatigue. An initial pilot involving 7 participants over 5 weeks suggested that fortnightly frequency was feasible but most participants were able to recall events over a four-week period.

A 1-page letter was created inviting participation in the project, with the only limitation being resident age. The letter informed potential participants (i) of the aims of the study, (ii) that temperature sensors would be placed in their home between November 2016 and September 2018, (iii) that they would be asked to answer thermal comfort and health questionnaires on a monthly basis, and (iv) that they would have the right to withdraw from the study at any time.

Two methods of recruiting participants for the study were used:

- Random sampling: In order to minimise bias in the sample, a random sampling process was adopted. Twelve areas of Bath were selected, with two or three streets in each area targeted for the letters to be posted. Six hundred letters were posted in total through this process. Households expressing interest were either emailed further information (another 1 page letter detailing more information about timescales and project phases) or phone called, depending on their preference.
- Targeted sampling: To increase the likelihood of reaching an older demographic, presentations were undertaken to groups such as Age UK, University of the Third Age, Lunch Clubs and St. John's Care, in Bath. Each presentation lasted 30 minutes, followed by another 30 minutes of Q&A, with the chance to ask questions individually. Interested members of the audience were provided a letter incorporating the briefing letter and the further information letter as in the random sampling.

The random sampling process generated 25 participating homes (4.2% response rate), and the targeted sampling a further 18, bringing the study total to 43 participating homes with a total of 59 occupants. Each home designated one person to respond to the surveys to ensure continuity. All participants live within a three mile radius of Bath. The mean age of our sample is 76.3 years ($n = 59$, $s = 9.1$ years).

Appendix B Sensor Selection

For the measurement of air temperatures in the living and bedrooms, prior work in this area has suggested a minimum accuracy of 0.5°C or better [67, 68]. Maxim's iButton range (e.g.

the DS1922L-F5) or the HOBO UA-001-08 temperature sensors meet these requirements and are hence the most common choices for similar studies in the literature.

Both sensors were exposed to the likely range of real world temperatures through an initial test conducted in a climate chamber, comparing HOBO UA-001-08 sensors with iButton DS1922L-F5 sensors. The climate chamber was set to span a temperature range of 30°C at 30 minute intervals, between 5°C and 35°C, with relative humidity set at a constant 50%. The sensors were programmed to record every 10 seconds. The only sensor to span the full 30°C were the iButtons; the HOBO sensors measured a range of 25°C. As the iButton results suggested a more reliable reading they were chosen for the project.

B.1 Sensor Installation

Living room and bedroom sensors were located away from windows and local sources of heat, approximately 1.5 metres above the ground (e.g. on a shelf), in accordance with ASHRAE 55 Class I. Although further measuring using the Swema ISO compliant monitoring equipment meets the Class II requirements [69].

Figure legends

1. UK, South East and South West England summer mean external temperatures between 2001 and 2018. Horizontal lines and colours indicate UK (dashed, red), SE (dot-dashed, green) and SW (dotted, blue) means and standard deviations [64]. The purple area is the overlap between UK and SW standard deviations. Note that in the South West, 2017 was representative of an average summer whereas 2018 was well outside one standard deviation.
2. Figure 2: Hourly profile of summer 2017 and 2018, with 95% confidence interval (grey band).
3. Ranked median summer internal bedroom (BR) and living room (LR) temperatures for each house across 2017 (top, n=37) and 2018 (bottom, n=16). The black lines show group means for each room.
4. Ranked median internal humidity across both summers, with black line representing the mean.
5. Percentage of occupied hours (calculated according to TM59 criteria) exceeding a range of internal temperatures by room type and year. Living Rooms (LR) are in the top row, bedrooms (BR) in the bottom row with 2017 and 2018 in the left and right columns respectively. All graphs marked with 26°C threshold (dashed line) per TM59 guidance for bedrooms and PHE's Heatwave Plan for care homes (applied to Living Rooms in our data set). Note that the home with the identifiably different profile (e.g. in the 2018-BR plot) is a basement flat with high thermal mass and low solar gains.
6. Density plots for TSV and PMV, in summer 2017 (left) and summer 2018 (right).
7. Outdoor running mean temperatures (°C) and indoor operative temperature (°C) for all participating homes in summer 2017 (top) and 2018 (bottom), split by room type (LR = living room, BR = bedroom), with the ISO 15251 Category I (dotted), II

(dashed) and III (solid) limits. The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.

8. TSV for summer 2017 (left, N = 114) and summer 2018 (right, N = 48) with the ISO 15251 Category I (dotted), II (dashed) and III (solid) limits. Coloured numbers represent TSV vote ranging from +3 (deep red), through 0 (black) to -3 (deep blue). The vertical dot-dash line represents the minimum temperature for which the adaptive model claims validity.
9. TM59 Criterion 1A: Percentage of hours of exceedance per home for 2017 (black) and 2018 (grey) in the living room (left) and bedroom (right), with 3% threshold (dotted line). TM59 Criterion 1B: Percentage of bedroom hours above 26°C per home for both summers, with 1% threshold (dotted line).
10. TM59 Criterion 1B: Percentage of bedroom hours above 26°C per home for both summers, with 1% threshold (dotted line). Number of hours per home where the internal temperature was 4°C above the upper limit.
11. Number of days for each home where the daily weighted exceedance (Criterion 2) was not met.
12. Number of hours per home where the internal temperature was 4°C above the upper limit.

Appendix C: House Characteristics

<u>Housing Characteristic</u>		Percentage of Participants
<u>House Type</u>	Detached	23
	Semi-detached	33
	Terrace	23
	Flat	16
	Bungalow	5
House Age	Pre-1919	35
	1920-44	10
	1945-64	26
	1965-84	14
	1985+	15
Wall Type	Cavity	60
	Solid	40
Insulation	Yes	44
	No	56
Double Glazing	Yes	77
	No	23
Central Heating	Yes	97
	No	3
Openable Windows	Yes	100
	No	0

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